



# Control Design for an Advanced Geared Turbofan Engine

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# Outline

- Background and Objective
- Simulation Description
  - Engine Model
  - Controller Design
  - Actuator Hardware Model Design
- Mission Demonstration
- Sample Study
- Details on Model Operation
- Summary



## Background

- As preparation for the next generation of aircraft, advanced high-efficiency engine concepts have been developed to demonstrate new technology.

The Advanced Geared Turbofan, 30,000 lbf (AGTF30) engine simulation was developed to investigate possible next generation engine system designs including:

1. Ultra-high bypass
2. Small core
3. Variable area fan nozzle (VAFN)

- **Objective:**

- Detail the generation of a full envelope, classical control system for the AGTF30 engine.
- Highlight challenges associated with the control system concept of this advanced engine.

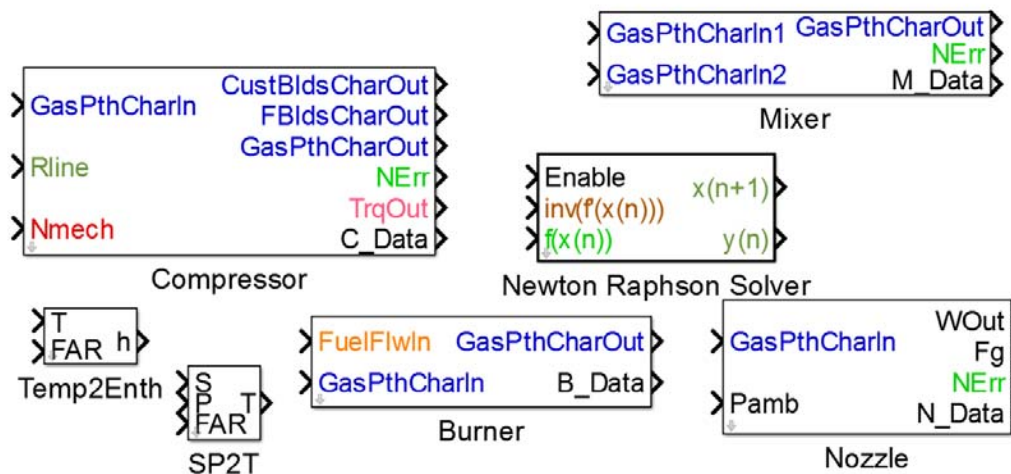
- **Purpose:**

- To provide a dynamic platform for next generation engine system research.



# Modeling Platform

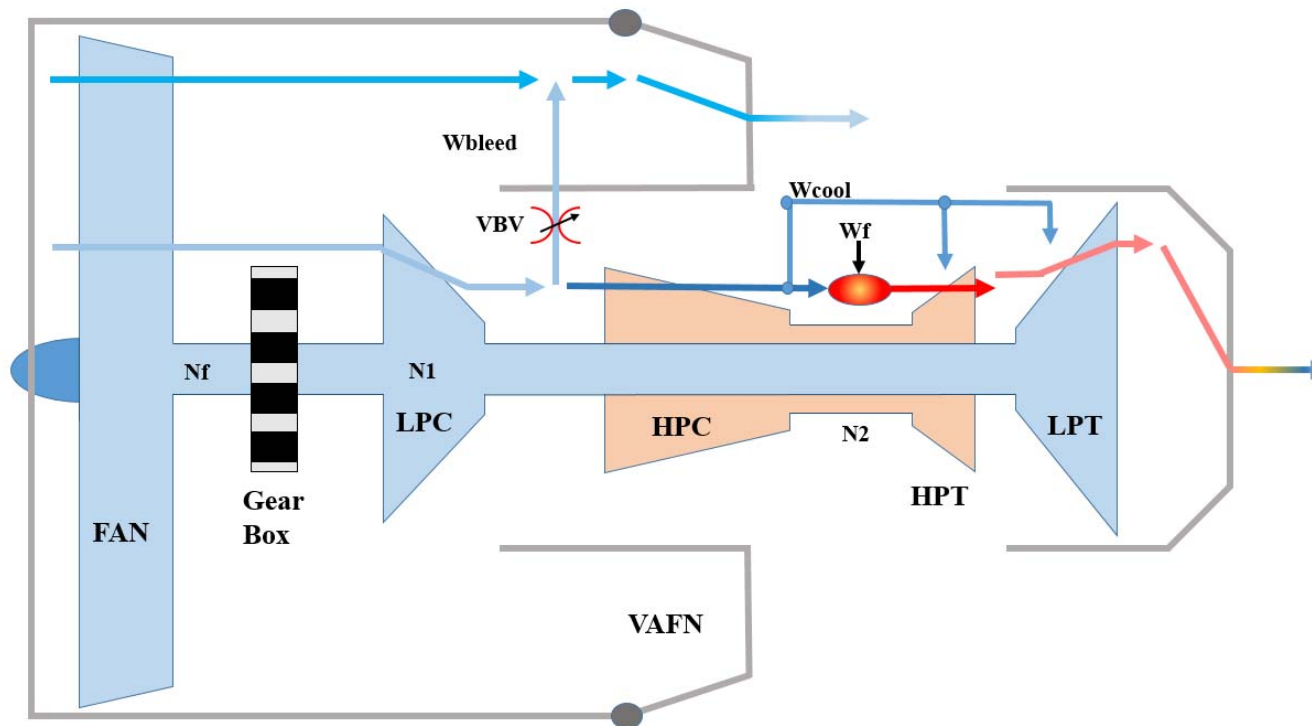
- The AGTF30 was created using the Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Modular thermodynamic modeling framework created by NASA
  - Built on top of MATLAB/Simulink
  - Package highlights:
    - General thermodynamic simulation design framework
    - Variable input system solvers
    - Advanced turbo-machinery block sets
    - Control system block sets
    - Non-proprietary, free of export restriction and open source with +4500 downloads, <https://github.com/nasa/T-MATS/releases>





# Engine Model Description

- **Advanced Geared Turbofan features**
  - Variable area fan nozzle (VAFN)
  - Dual spool with low pressure shaft connected to fan via a gear box
- **Performance**
  - BPR = 24, OPR = 50, TIT = 3000, TSFC = 0.46 at cruise
  - 30,000 lbf takeoff thrust
- **Control Effectors: VAFN, fuel flow ( $W_f$ ), and variable bleed valve (VBV)**

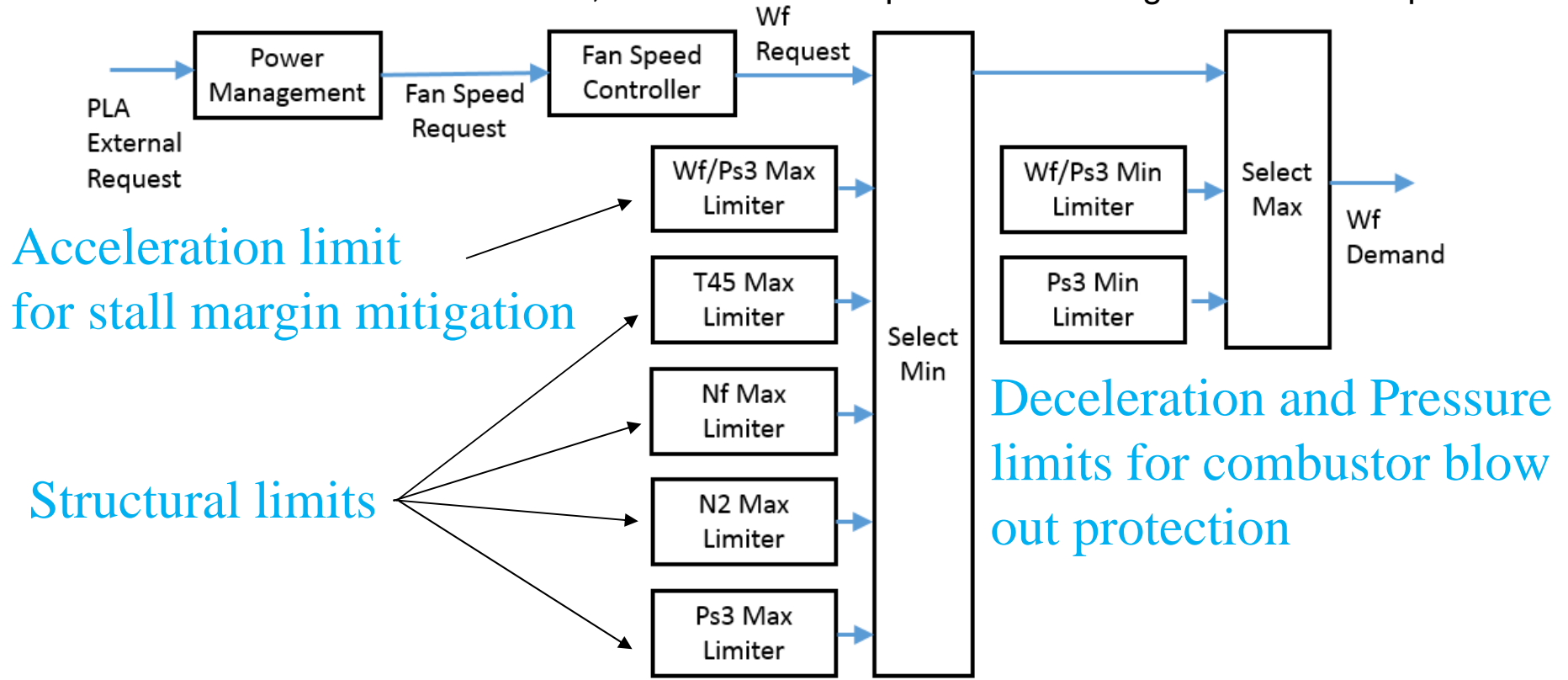




## Fuel Control Architecture

- Fuel Control methodology based on literature

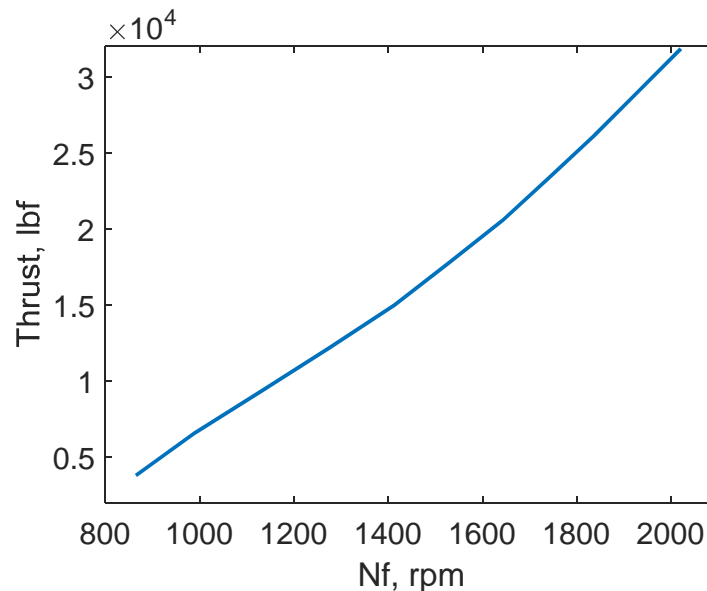
- Power Management generates fan speed request based on power lever angle (PLA)
- Fan speed controller generates a fuel flow request
- Sets of limiters adjust the fuel flow request to operate the engine safely, avoiding engine stall, exceeding structural limits, combustor blowout, etc.
- Controllers utilize PI method, tuned to meet requirements throughout the envelope





# Fuel Control Power Management

- Fuel is the main effector to control the engine, and thrust is the dominant engine output.
- AGTF30 utilizes a classical control strategy
  - Thrust cannot be sensed, so fan speed (Nf) was selected as the thrust surrogate
  - Advantages of using fan speed:
    - Generally linear relationship with thrust (given constant environment and consistent variable geometry positions).
    - Sensor availability and low susceptibility to noise

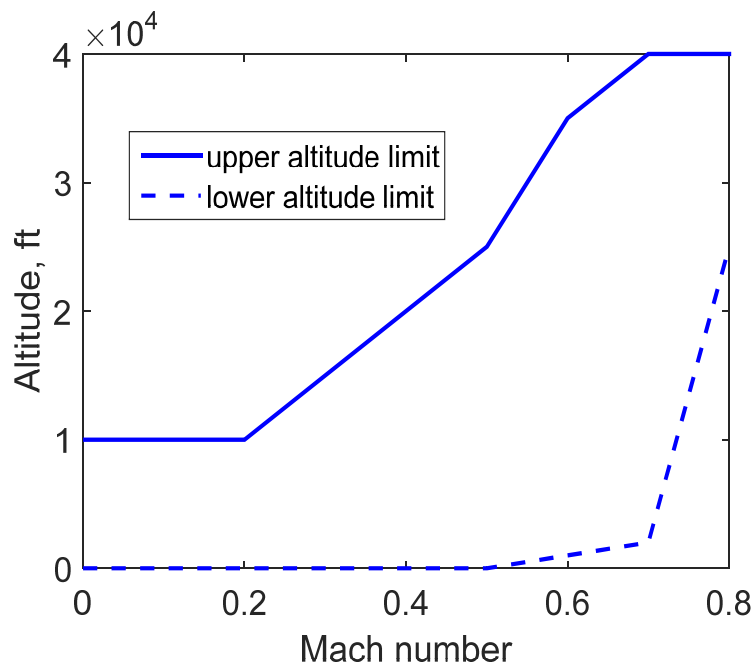


Relationship between  
Thrust and Nf sea level and  
static conditions

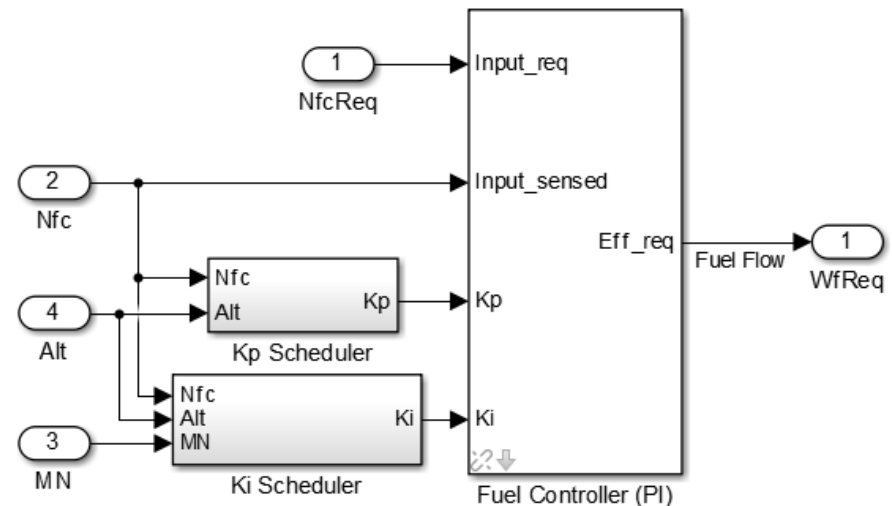


## Fuel Control Tuning

- **PI controller gains tuned to ideal values throughout envelope**
  - Linear models were generated throughout the envelope and at various power levels
  - PI controller gains were tuned for each defined linear model.
  - Gains were collected into schedules that provide the optimum gain at each operational point.



Operational Envelope



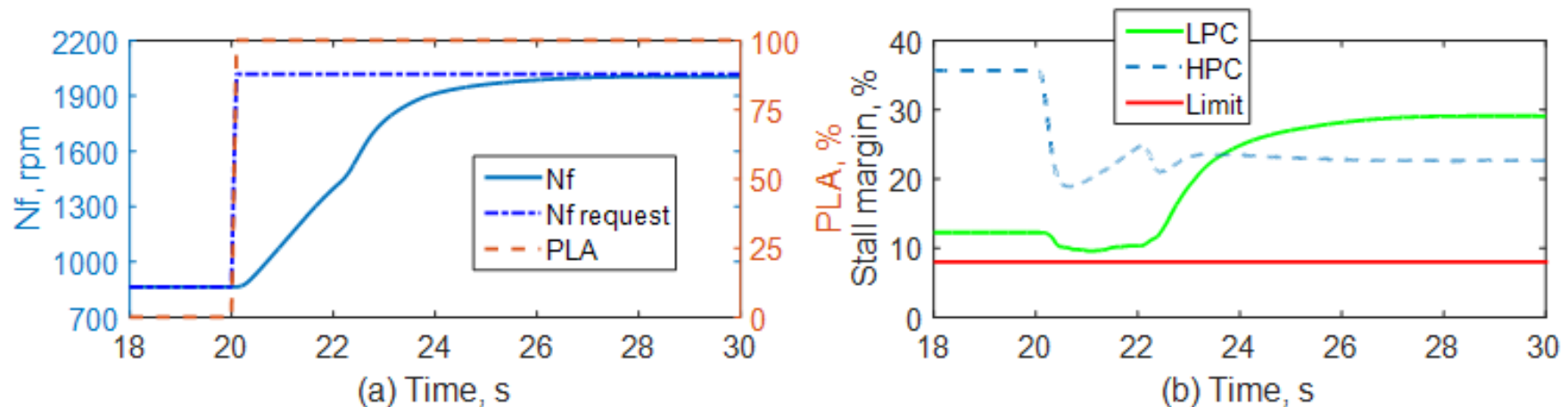
Speed Controller





## Setting Fuel Limiters

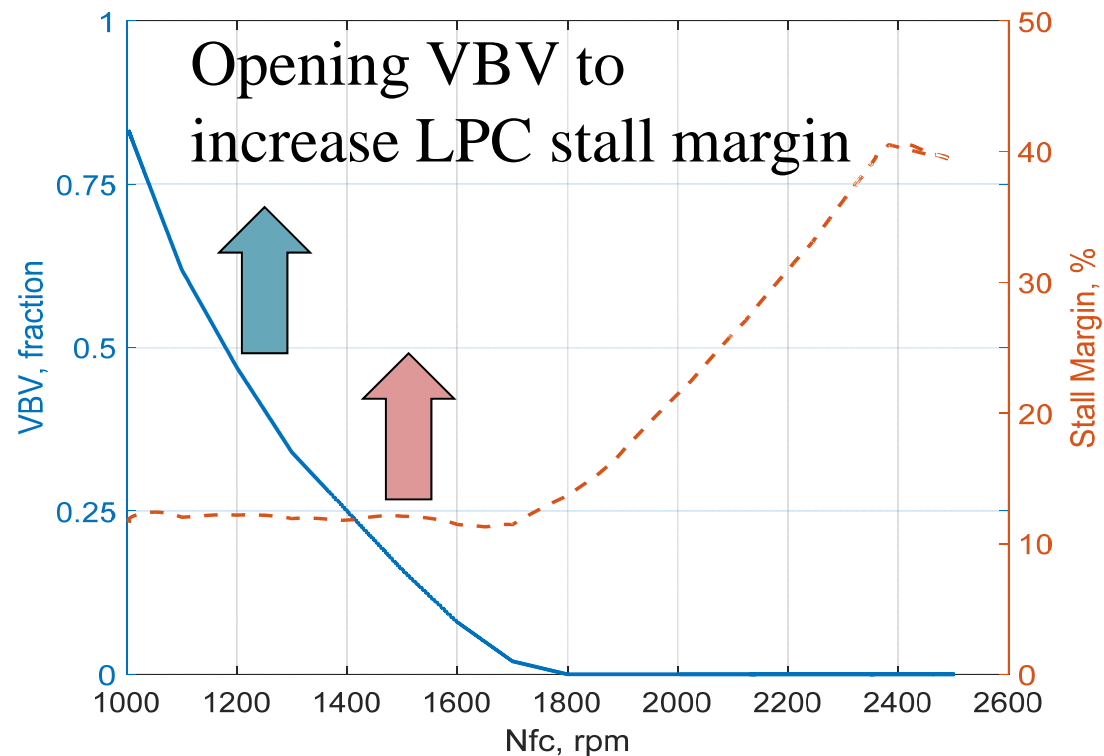
- Limiters designed to maintain safe engine operation
  - Set to avoid engine stall, structural limits, and engine blow out.
    - Structural limits based on anticipated next generation requirements.
    - Stall mitigated by limiting acceleration with a maximum  $Wf/Ps3$  limit
    - Hypothetical engine blow out mitigated with minimum  $Wf/Ps3$  and  $Ps3$  limits
  - Limiters tuned to allow acceleration from idle to 95% takeoff power within 5 seconds
  - Minimum stall margin requirement set to 8%.





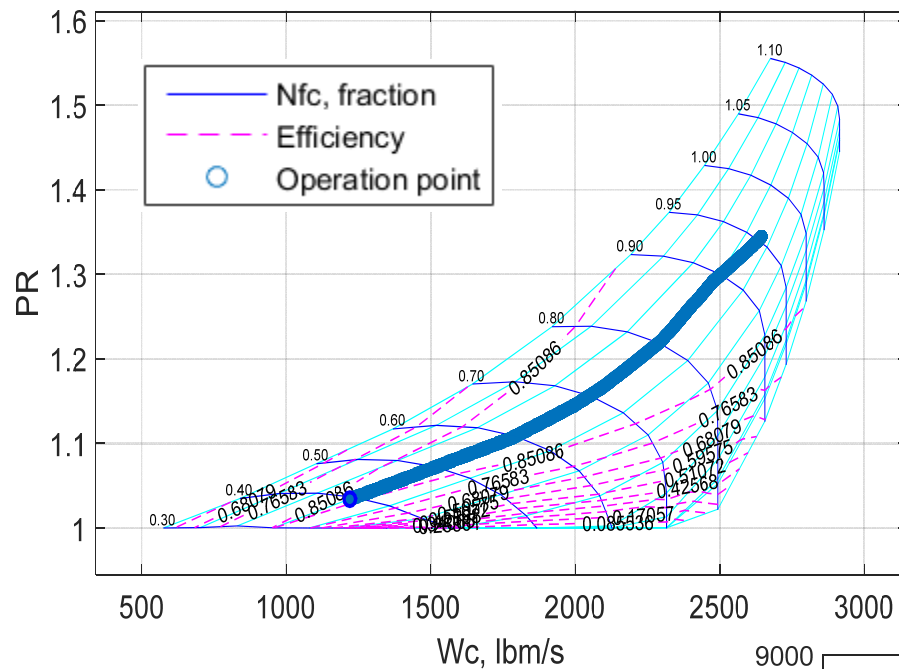
## VBV Control Architecture

- Variable bleed valve opens to reduce low pressure compressor (LPC) pressure ratio (PR), increasing stall margin.
  - Schedules constructed to maintain 10% stall margin during steady-state operation.





# VAFN Control Architecture

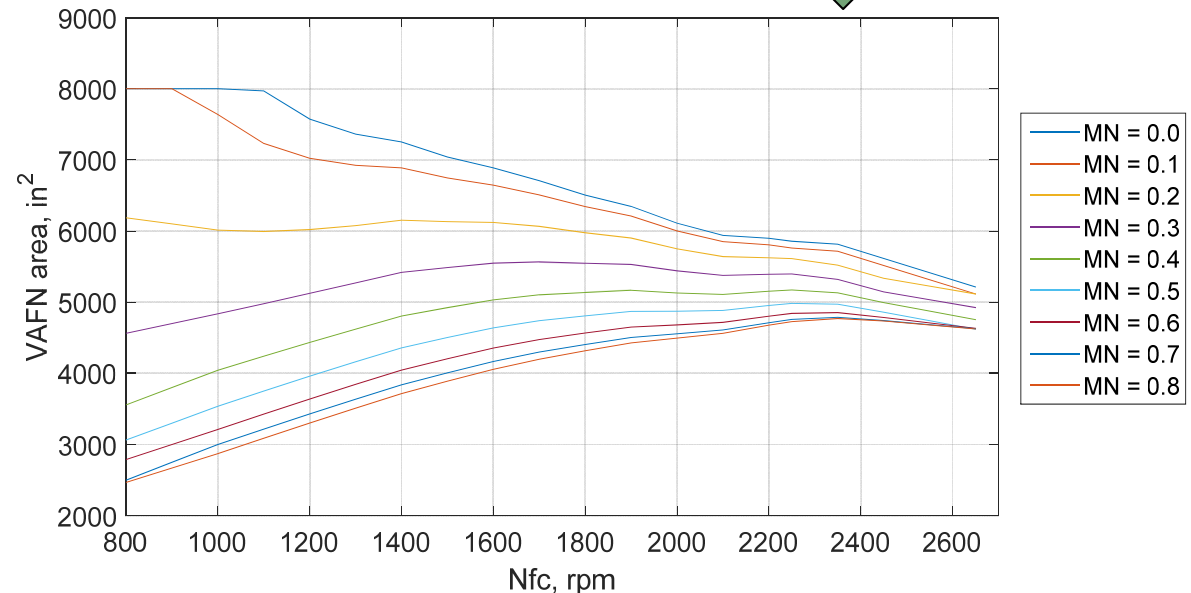


Fan Performance

Optimal efficiency

VAFN Schedule

- Variable area fan nozzle area scheduled to maintain optimal fan efficiency.
  - Nozzle area increased to reduce fan PR
  - Nozzle area decreased to increase fan PR





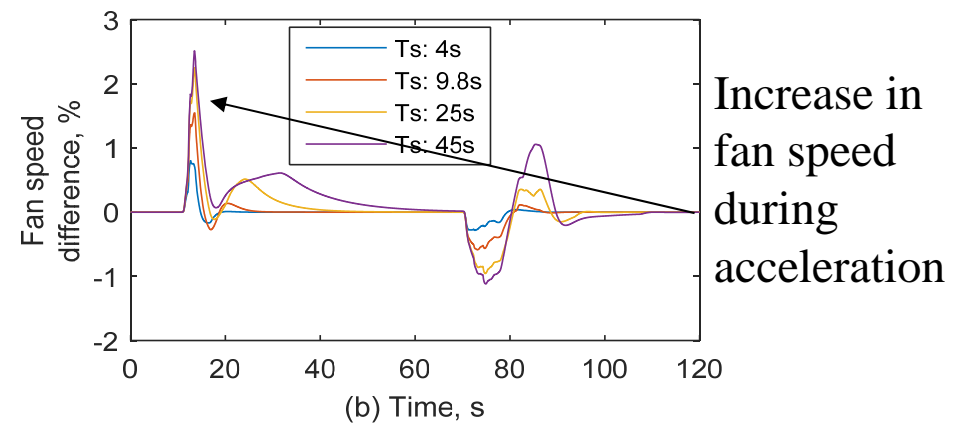
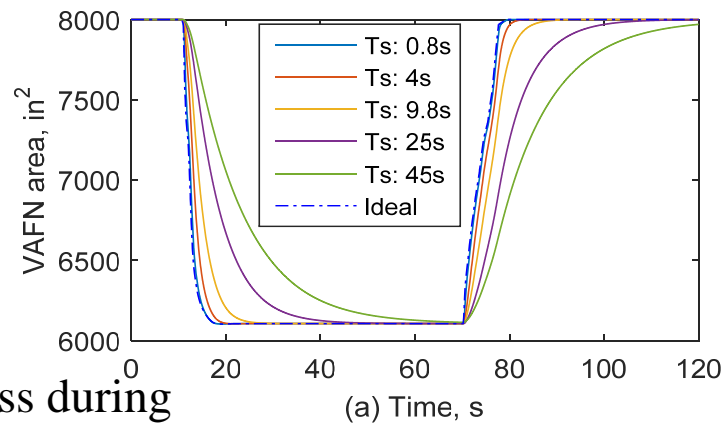
## Actuator Modeling

- Fuel metering valve (FMV)
  - First order actuator with a dynamic response much faster than rotor dynamics
- Variable bleed valve (VBV)
  - First order actuator with a dynamic response much faster than rotor dynamics
- Variable area fan nozzle (VAFN)
  - Research into VAFN actuation is ongoing
  - Thermally activated shape memory alloy is being considered as a solution
    - Advantages
      - High power-to-weight ratio
    - Challenges
      - Maximum area reduction may not meet ideal nozzle requirements
      - Slew rate may not meet engine transient requirements.
      - Low technology readiness level (TRL)
  - Due to uncertainty in actuator characteristics the AGTF30 utilizes an idealized actuation system as default, settling time equivalent to 0.8s. This value will be updated as more research becomes available.

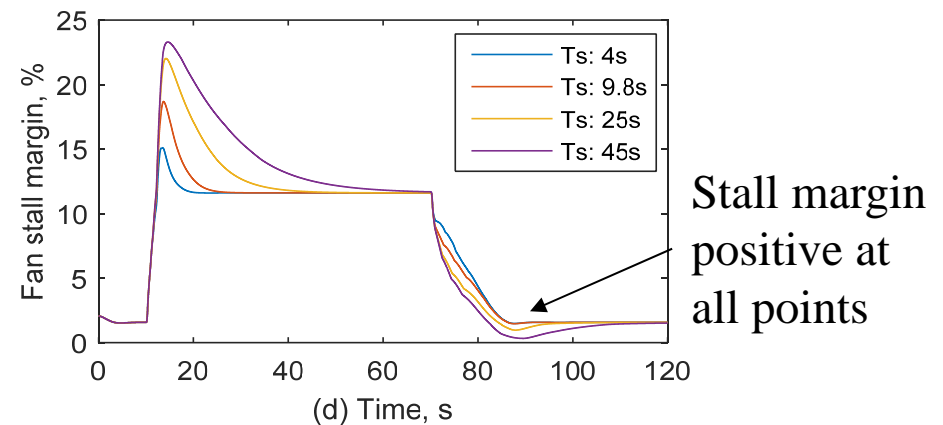
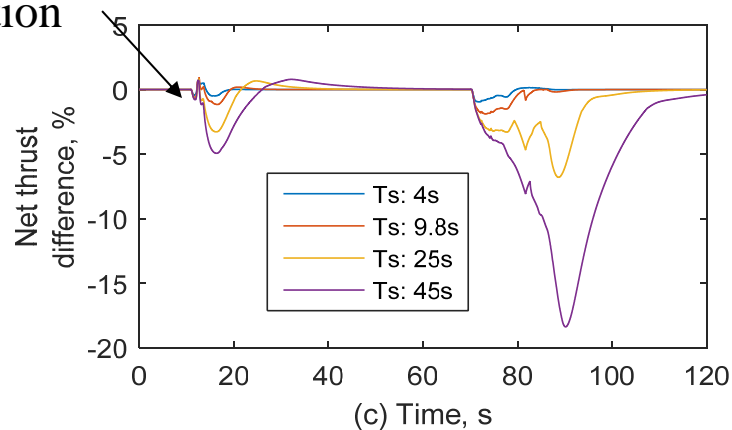


## VAFN response study

- The AGTF30 was used for a simple study to find the minimum settling time requirement for a hypothetical shape memory alloy actuator.
  - Traces show acceleration from Idle to Full power then a deceleration back to idle
  - Plots b and c show divergence from ideal actuation (tracks control request perfectly)



Thrust loss during acceleration

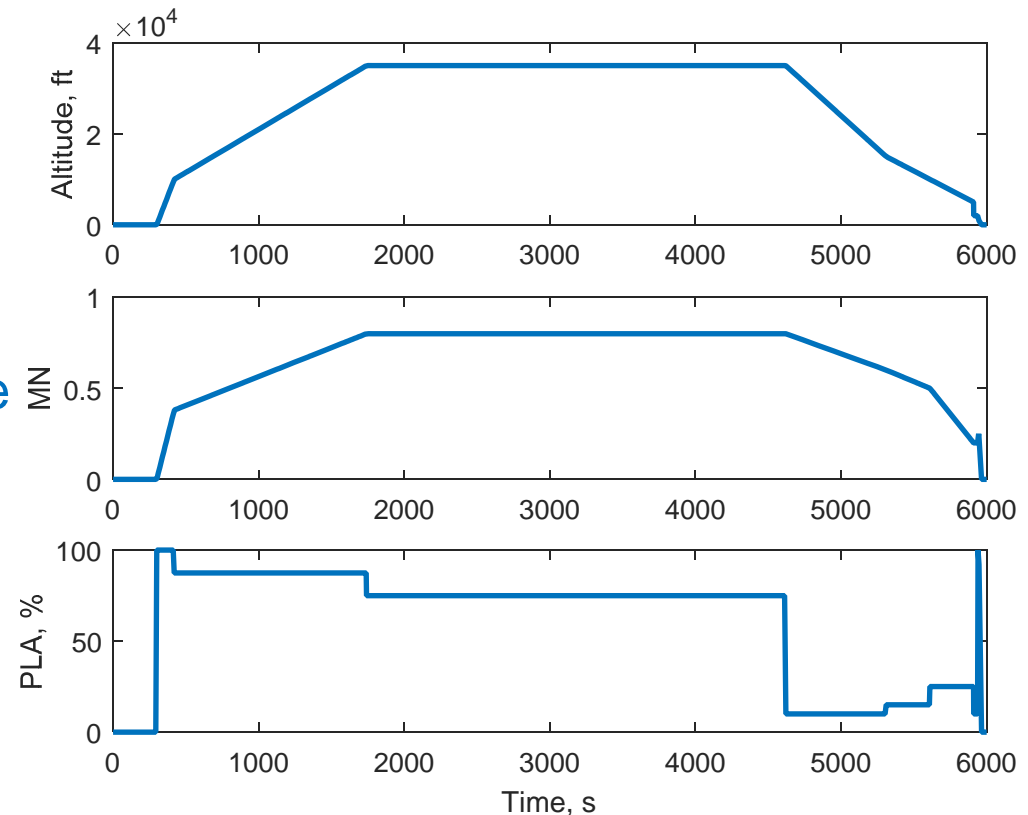


Settling times greater than 9.8s, generate large losses of thrust



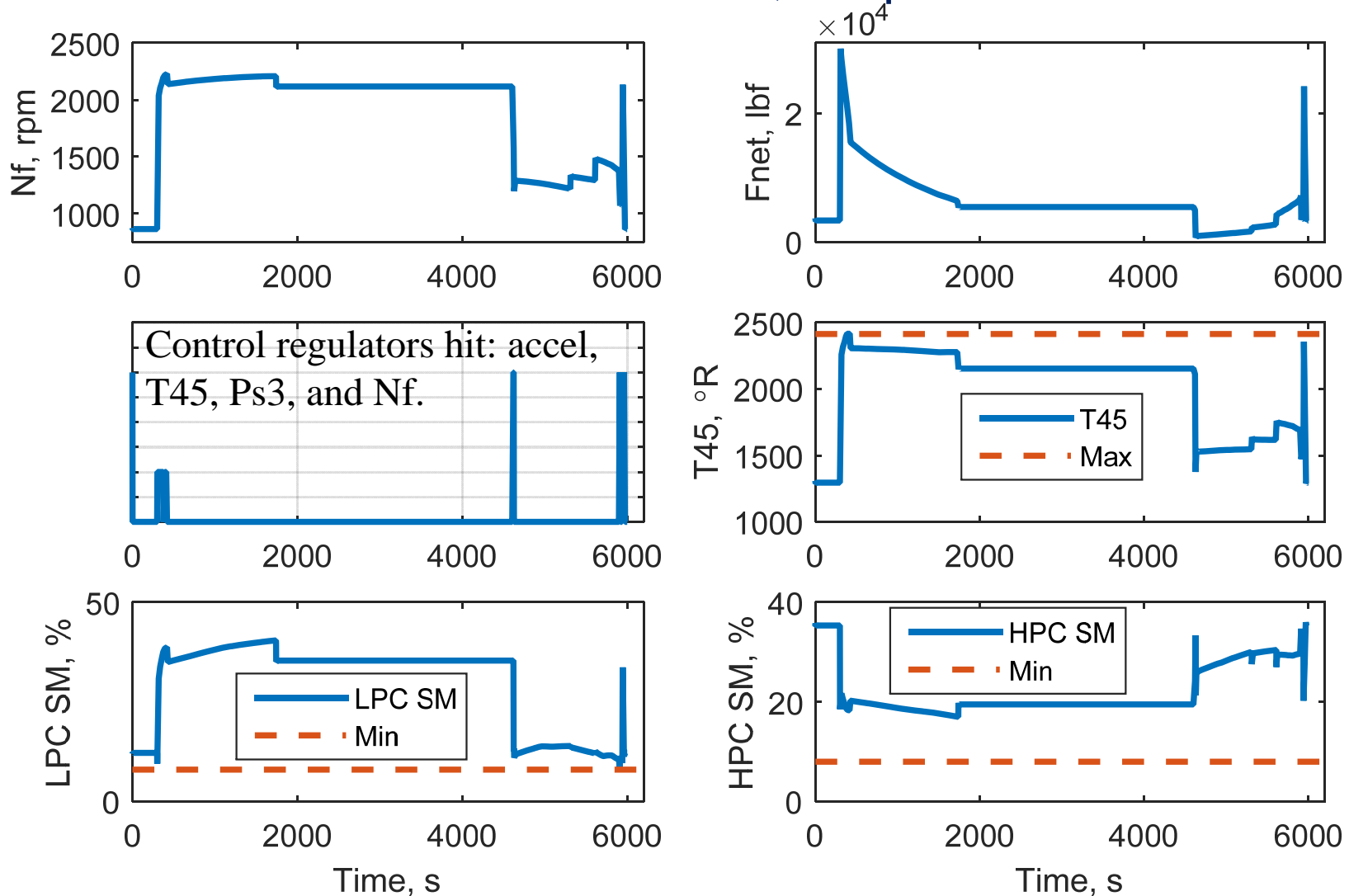
# Model Validation

- Engine Model validation
  - Simulation of an abbreviated mission profile
    - Engine idling
    - Acceleration from idle to full power followed by a take off at sea level static conditions
    - Engine climbs to cruise at 35,000 ft
    - Deceleration and descent
    - Aircraft lands then returns to idle





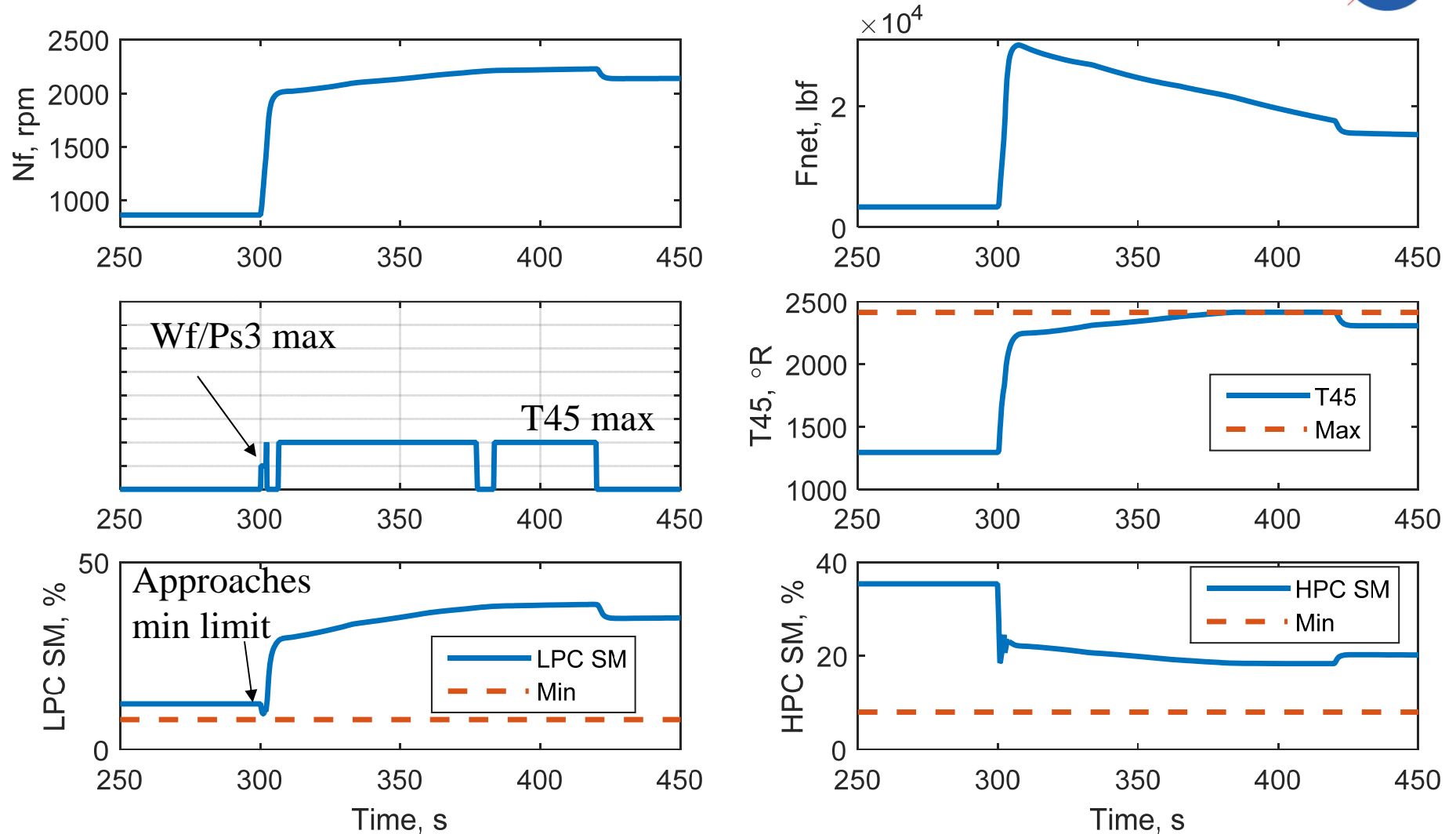
## Model Validation, full profile



For the validation profile, all parameters remain within acceptable parameters and the engine performs as expected



## Model Validation, takeoff and climb

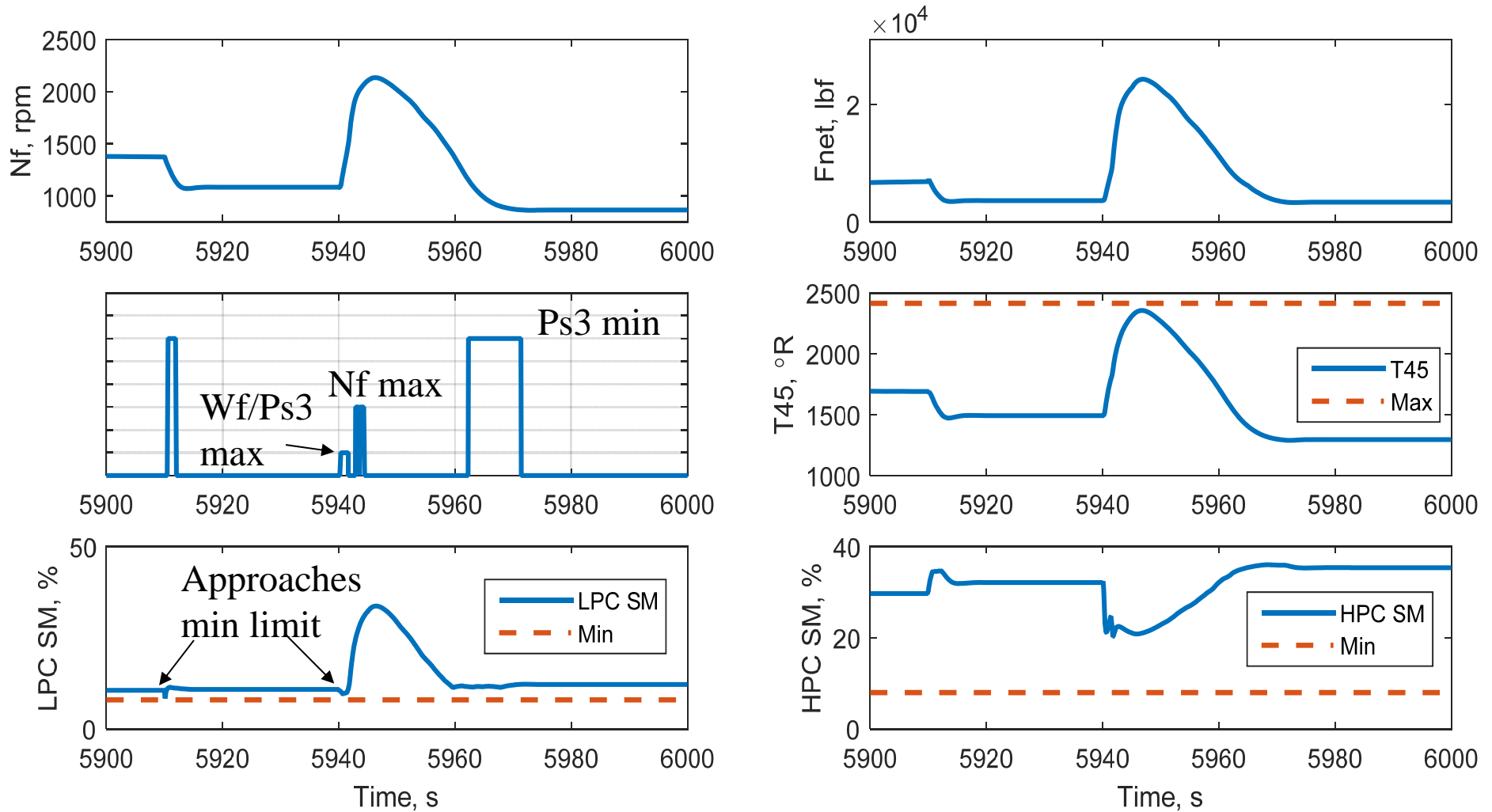


During acceleration and climb to altitude the control regulators act to maintain stall margin and maximum T45 limit





# Model Validation, approach and landing



During approach and landing the control regulators act to maintain stall margin, maximum Nf limit and minimum Ps3 limit



# Simulation Operation

Current Folder

Name	Description
+AGTF30	AGTF30 class definition
SimSetup	Folder containing setup files
AGTF30_eng.slx	Engine Model
AGTF30SysDyn.slx	Steady-State, Dynamic, and Linearization models, all use the same Engine Model file
AGTF30SysLin.slx	
AGTF30SysSS.slx	
define_inputs.m	Link to input definitions
define_inputs.xlsx	Excel spread sheet for quick input definition
PlotDyn.m	Plotting scripts
PlotSS.m	
setup_cleanup.m	Simulation setup and clean up scripts
setup_everything.m	













## Setup Everything

MWS =

```
engName: 'AGTF30'
top_level: 'C:\AGTF30'
  POp: '\'
  Cntrl: [1x1 struct]
iDesign: 2
  Inlet: [1x1 struct]
    FAN: [1x1 struct]
    LPC: [1x1 struct]
    HPC: [1x1 struct]
    HPT: [1x1 struct]
    LPT: [1x1 struct]
    VBV: [1x1 struct]
  Burn: [1x1 struct]
  NozByp: [1x1 struct]
  NozCor: [1x1 struct]
  Duct: [1x1 struct]
  GearBox: [1x1 struct]
  Sensor: [1x1 struct]
    Act: [1x1 struct]
  Shaft: [1x1 struct]
    In: [1x1 struct]
```

Setup\_everything.m - Loads bus objects and MATLAB Workspace (MWS) structure containing all simulation inputs

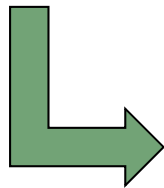
	Amb	1x1 Bus
	BackEng	1x1 Bus
	BypassEng	1x1 Bus
	CoreEng	1x1 Bus
	FAN_Data	1x1 Bus
	FrontEng	1x1 Bus
	HPC_Data	1x1 Bus
	HPT_Data	1x1 Bus
	LPC_Data	1x1 Bus
	LPT_Data	1x1 Bus



## Input File

- Enter inputs manually

```
%% Set default time vector name
DefTVNm = 't';
% Set default time vector values
MWS = SetInput(MWS, DefTVNm, [0 10 20 20.1 50], inputs);
```



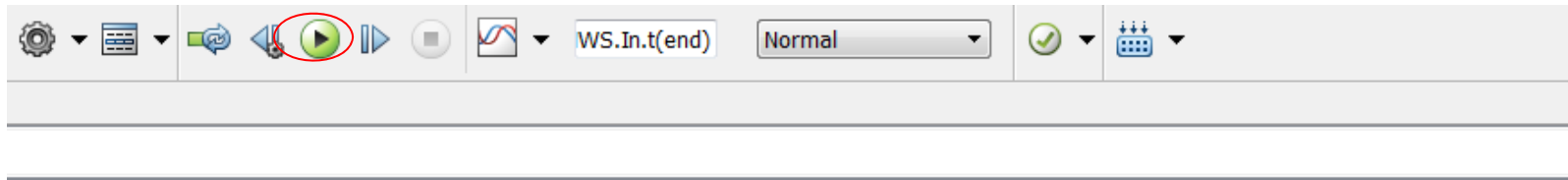
```
% PLA or Power Code (40 to 80.5)
MWS = SetTVec(...
    MWS, 'PLA', ...
    [40 40 40 80 80], ...
    DefTVNm, inputs);
```

- Or use an excel spread sheet

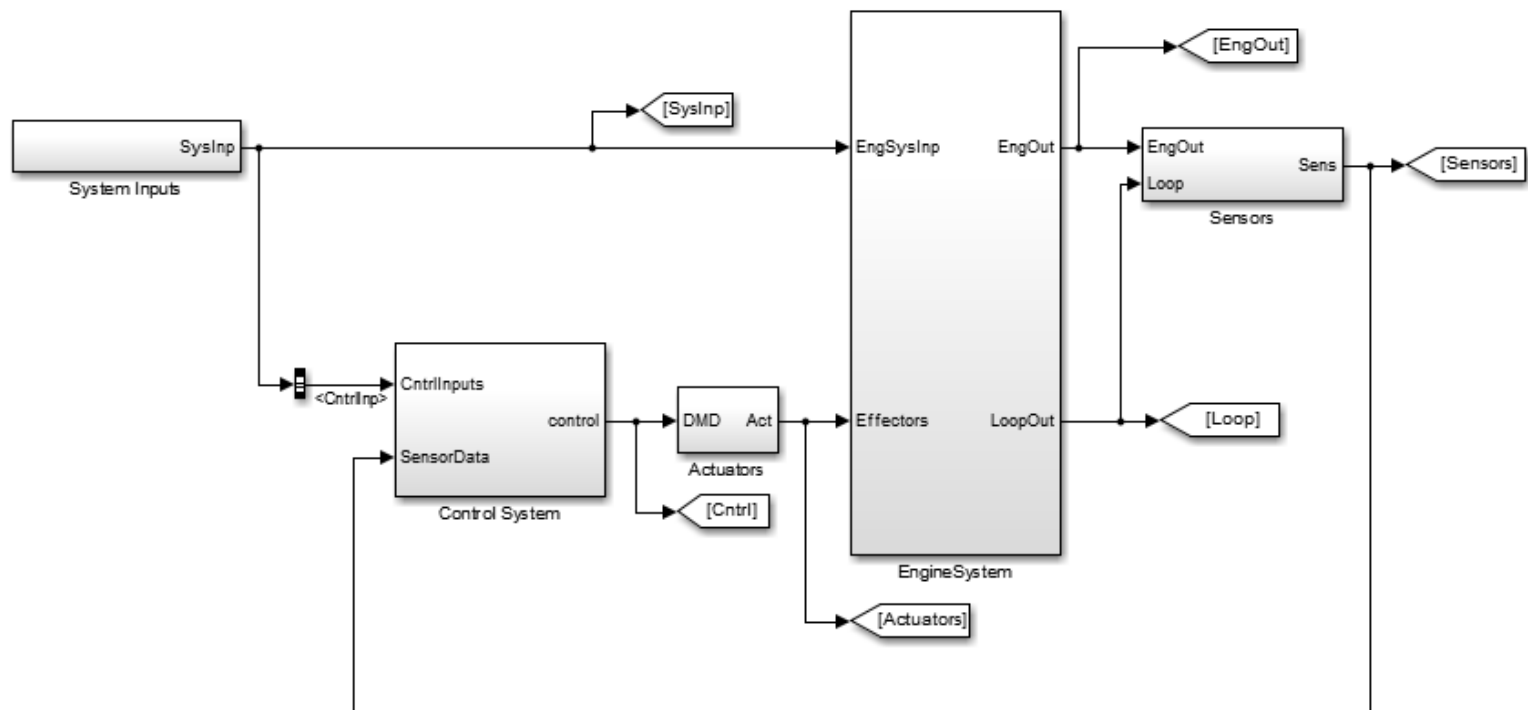
	A	B	C	D	E	F	G	H
1	Description	Input Variable	Associated Time Vector	Data:				
2	time (s)	t	NA	0	10	20	20.1	50
3	Altitude (ft)	Alt	t	0				
4	Mach Number	MN	t	0				
5	Delta Temperature (degF)	dT	t	0				
6	PLA (deg)	PLA	t	40	40	40	80	80



## Running the Model



# Dynamic AGTF30 Advanced Geared Turbofan Engine System





## Data Presentation

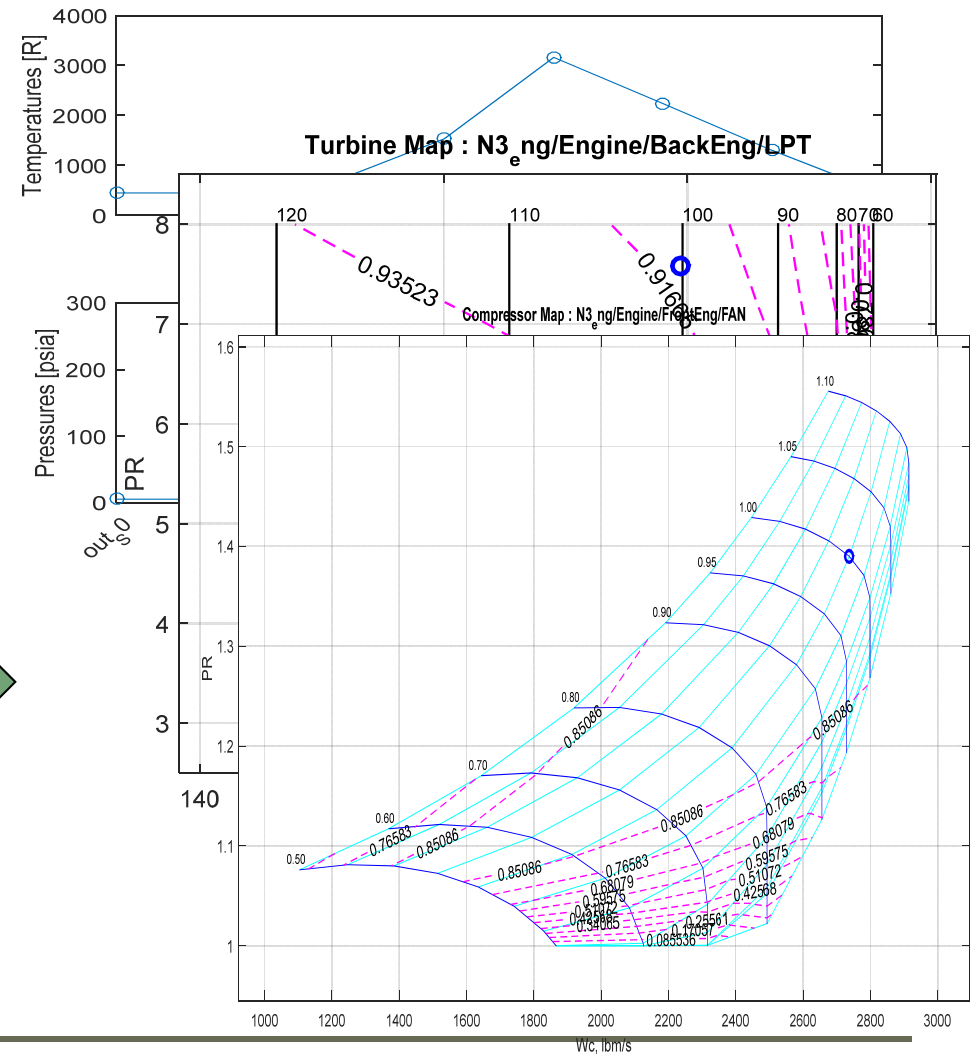
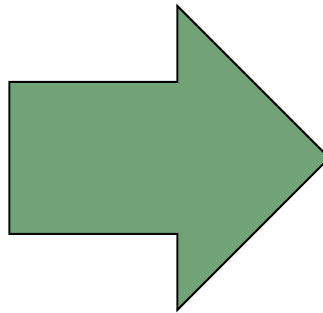
```
>> out_Dyn
```

```
out_Dyn =
```

```
act: [1x1 struct]
cntrl: [1x1 struct]
eng: [1x1 struct]
loop: [1x1 struct]
sen: [1x1 struct]
in: [1x1 struct]
```

Data gathered in an  
output structure.

Formatted to  
make use of  
T-MATS auto  
plotting tools





## Summary

- A simulation of a next generation engine has been presented
  - Advanced Geared Turbofan 30,000lbf (AGTF30)
    - Ultrahigh bypass, small engine core, VAFN design
    - Full envelope dynamic control system
    - Built with the Toolbox for the Modeling and Analysis of Thermodynamic systems (T-MATS), <https://github.com/nasa/T-MATS/releases>
    - Simulation awaiting approval to be made publically available
- Control system design described
  - Fuel control based on classical architecture
  - Variable geometries scheduled
- Sensitivity study on VAFN slew rate
  - Shape memory alloy is currently being considered for use as the VAFN actuator, and actuator slew rate has been shown to be a limiting factor.
  - Analysis of ideal and potential slew rates show significant performance degradation at actuator settling times greater than 9.8s
- AGTF30 simulation meets all requirements
  - Simulation provides a realistic and dynamic platform for research into advanced geared turbofan technologies.



## Acknowledgments

Funding for this work was provided by NASA  
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